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ON THE RELATION OF THE HALL EFFECT TO THE CURRENT DENSITY IN GOLD.

By THOMAS C. MCKAY.

Presented by E. H. Hall, June 17, 1903. Received December 10, 1903.

THIS subject was suggested to the writer by Professor Hall. The work was carried on under his supervision in the Jefferson Physical Laboratory of Harvard University. The subject was taken up as a consequence of a paper of Moretto,* published about four years ago, in which measurements of the Hall effect over a very large current range were described, and results obtained at variance with the generally held theory of the phenomenon. The results of previous investigators are given first, with a general account of their work, in order that the subject of inquiry may be clearly set forth.

The first observations on this subject were made by Professor Hall,† on the plate with which he discovered the general law of the phenomenon. This was a strip of gold leaf, about 9 centimeters long and 2 centimeters wide, mounted on a piece of plate glass. Contact was made with the ends of the strip by pressing on them two pieces of polished brass. These were connected to the terminals of a Bunsen cell. The terminals of a high resistance Thomson galvanometer were connected to two opposite points on the edges of the strip about midway between the pieces of brass. The glass plate bearing the gold was cemented to the flat end of one pole of the electromagnet and the other pole brought to within 6 millimeters of the strip. The following results were obtained:—

<i>C.</i>	<i>M.</i>	<i>c.</i>	$\frac{C \times M}{c}$
.0616	11420 <i>H</i>	2.32×10^{-9}	3.03×10^{11}
.0249	11240 <i>H</i>	0.85×10^{-9}	3.29×10^{11}
.0389	11060 <i>H</i>	1.35×10^{-9}	3.19×10^{11}
.0598	7670 <i>H</i>	1.47×10^{-9}	3.12×10^{11}
.0595	5700 <i>H</i>	1.04×10^{-9}	3.26×10^{11}

* Moretto, Nuovo Cimento, Serie 4, **11**, 278-289 (1900).

† American Journal of Mathematics, **2**, 287-292 (1879).

H is the horizontal intensity of the earth's field, about 0.19; C is the strength of the primary current; M is the strength of the magnetic field; c is the current through the Thomson galvanometer.

This showed the general law of the phenomenon for a plate of a given thickness, since it showed $\frac{C \times M}{c}$ to be at least approximately a constant within the range of primary current used.

Righi * made a series of measurements maintaining the magnetizing current constant. He used gold, which he prepared according to the method of Professor Hall. He found the effect observed proportional to the current, except for weak currents, for which the effect was relatively greater. The differences were always very small and Righi thought that they might have been due to some unknown error. The tabulated results are not given in his paper.

Leduc † made a similar series of experiments on bismuth. The transverse difference of potential caused by the introduction of the magnetic field was measured with a capillary electrometer. The following table of results is given.

C .	I .	E .	$\frac{E}{CI} \times 10^6$.
5.77	5.127	0.01248	421
5.98	3.572	0.00895	419
5.97	2.119	0.00531	420
5.93	1.386	0.00343	417
5.92	0.823	0.00205	421
5.90	0.647	0.00159	417
5.87	0.330	0.00081	419
			Mean, 419

C is the intensity of the current in the electromagnet; I is the intensity of the primary current in the plate; E is the difference of potential at the secondary electrodes, caused by the magnetic field.

* Memorie della Accademia delle Scienze di Bologna, p. 115 (1883).

† Comptes Rendus, **98**, 673-675.

The expression $\frac{E}{CI}$ is here seen to be practically constant over the range used.

Moreau* made a series of measurements in very thin silver and nickel plates. These metals were deposited on glass plates. The following results were obtained with a silver plate, in which the main current was varied while the magnetic field was kept constant:

		$E = 81 \mu\mu$						
		$H = 3300$						
I	70	57.2	50.4	41.5	37.3	27.2	24.5	18.2
Δ_1	127	103	92	74	67	48	44.5	32
$\frac{\Delta_1}{I}$	1.81	1.80	1.82	1.78	1.79	1.76	1.80	1.76

E is the thickness of the plate in millionths of a millimeter; I is the strength of the primary current in milliamperes; Δ_1 is the deviation of

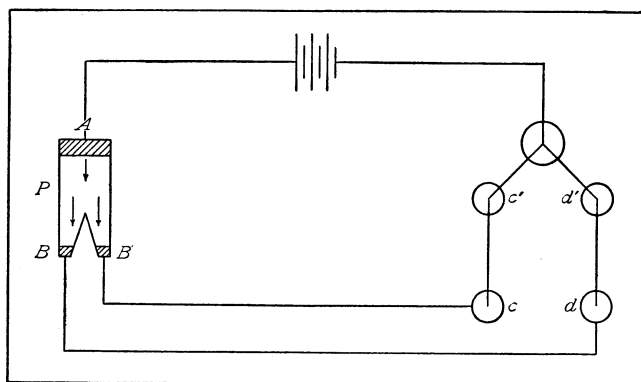


FIGURE 1.

the galvanometer in the secondary circuit; H is the strength of the magnetic field.

The greatest range of primary current seems to have been obtained by Moretto.† The only metals which he mentions in his paper as having

* Journal de Physique, Serie 3, **10**, 478-493 (1901).

† Nuovo Cimento, Serie 4, **11**, 278-289.

* Moreau also investigated the influence of the thickness of the metal plate. He found that when the thickness of the plate was reduced below $44 \mu\mu$ the Hall effect was less than the value calculated from measurements of thick plates.

It has been observed by various experimenters that the Hall effect in gold leaf is less than that of thick gold.

been worked upon are gold and bismuth. In preparing these for the measurement of the Hall effect he used the form of plate employed extensively by Righi; see P, Figure 1.

Thus the current entering the plate at *A* was divided into the two partial currents at *B* and *B*. On the introduction of the magnetic field one partial current was increased at the expense of the other above its normal value, but correspondingly decreased on the reversal of the field.

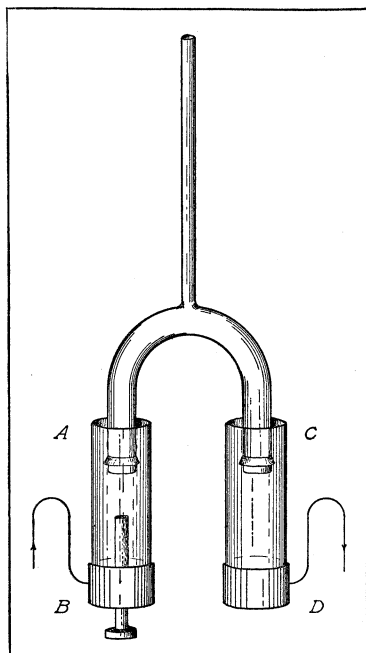


FIGURE 2.

At *c* and *c'*, *d* and *d'*, connection was made with the voltmeters which were placed in each branch. The voltmeters were of the following form. See Figure 2.

The jar *AB* contained a saturated solution of copper sulphate, the jar *CD* a solution of ten per cent by weight of sodium sulphate. The ends of the curved tube were covered with pieces of animal membrane. It was filled with a solution of sodium sulphate. The current was made to pass from the copper sulphate solution to the sodium sulphate solution. The amount of sodium hydroxide formed at the cathode was measured by a method of volumetric analysis suggested by Cardani,* for use in measuring the quantity of electricity in the discharge of a condenser.

Cardani added measured quantities of a $\frac{1}{200}$ normal oxalic acid solution to a nine per cent sodium chloride solution which had been around the cathode while the current was passing. Using phenolphthalein as indicator, he endeavored to obtain by titration the same degree of redness as was shown by the original weakly alkaline sodium chloride solution before the passage of the current. In Moretto's work the strengths of the two partial currents were measured, first without the

* Nuovo Cimento, Serie 4, 7, 105 (1898); also Zeitschrift für physikalische Chemie, 27, 378 (1898).

magnetic field, again with the magnetic field in a given direction, then with the magnetic field in the opposite direction, and lastly without a field. A numerous series of determinations was made which gave results of the kind indicated by the following table, the only table of results bearing on our question in Moretto's paper.

STRENGTH OF FIELD — 9600 C. G. S. UNITS.

I Amperes.	Without Field.	Field in a given Direction.	Field in opposite Direction.	w Amperes.	$\frac{w}{I}$
0.2820	$\left\{ \begin{array}{l} q_1 \text{ 4.300} \\ q_2 \text{ 4.480} \end{array} \right\}$	$\left\{ \begin{array}{l} 4.315 \\ 4.465 \end{array} \right\}$	$\left\{ \begin{array}{l} 4.285 \\ 4.495 \end{array} \right\}$	0.00096	34×10^{-4}
0.1149	$\left\{ \begin{array}{l} q_1 \text{ 7.085} \\ q_2 \text{ 7.230} \end{array} \right\}$	$\left\{ \begin{array}{l} 7.110 \\ 7.250 \end{array} \right\}$	$\left\{ \begin{array}{l} 7.060 \\ 7.255 \end{array} \right\}$	0.000401	34×10^{-4}
0.0459	$\left\{ \begin{array}{l} q_1 \text{ 8.420} \\ q_2 \text{ 8.755} \end{array} \right\}$	$\left\{ \begin{array}{l} 8.450 \\ 8.725 \end{array} \right\}$	$\left\{ \begin{array}{l} 8.390 \\ 8.785 \end{array} \right\}$	0.000161	35×10^{-4}
0.0164	$\left\{ \begin{array}{l} q_1 \text{ 3.045} \\ q_2 \text{ 3.100} \end{array} \right\}$	$\left\{ \begin{array}{l} 3.058 \\ 3.088 \end{array} \right\}$	$\left\{ \begin{array}{l} 3.034 \\ 3.112 \end{array} \right\}$	0.0000642	39×10^{-4}
0.0129	$\left\{ \begin{array}{l} q_1 \text{ 2.115} \\ q_2 \text{ 2.710} \end{array} \right\}$	$\left\{ \begin{array}{l} 2.124 \\ 2.700 \end{array} \right\}$	$\left\{ \begin{array}{l} 2.106 \\ 2.720 \end{array} \right\}$	0.0000509	40×10^{-4}
0.00445	$\left\{ \begin{array}{l} q_1 \text{ 4.390} \\ q_2 \text{ 4.475} \end{array} \right\}$	$\left\{ \begin{array}{l} 4.408 \\ 4.458 \end{array} \right\}$	$\left\{ \begin{array}{l} 4.370 \\ 4.494 \end{array} \right\}$	0.0000186	42×10^{-4}
0.000645	$\left\{ \begin{array}{l} q_1 \text{ 1.985} \\ q_2 \text{ 2.030} \end{array} \right\}$	$\left\{ \begin{array}{l} 1.995 \\ 2.022 \end{array} \right\}$	$\left\{ \begin{array}{l} 1.976 \\ 2.039 \end{array} \right\}$	0.00000289	44×10^{-4}
0.000616	$\left\{ \begin{array}{l} q_1 \text{ 1.880} \\ q_2 \text{ 1.955} \end{array} \right\}$	$\left\{ \begin{array}{l} 1.890 \\ 1.948 \end{array} \right\}$	$\left\{ \begin{array}{l} 1.872 \\ 1.964 \end{array} \right\}$	0.00000273	45×10^{-4}
0.0000285	$\left\{ \begin{array}{l} q_1 \text{ 2.115} \\ q_2 \text{ 2.435} \end{array} \right\}$	$\left\{ \begin{array}{l} 0.916 \\ 1.038 \end{array} \right\}$	$\left\{ \begin{array}{l} 0.862 \\ 1.005 \end{array} \right\}$	0.000000155	54×10^{-4}

q_1 and q_2 are the quantities in cubic centimeters of a $\frac{1}{200}$ th normal solution of sodium hydrate, formed by the passage of the two partial currents respectively; I is the main current, and equal to the sum of the two partial currents; w is obtained by taking the difference made in each partial current by reversing the field, summing these differences, and dividing by 2. Moretto does not state the metal used in obtaining this series of results. It was probably bismuth.

The measurement of w depended on a small difference of the partial currents, which were not measurable with the highest accuracy. An

accuracy of one-tenth of a per cent in the measurement of four cubic centimeters of a $\frac{1}{200}$ normal solution by volumetric analysis would be very good work. In the opinion of the two instructors in chemistry consulted by the writer, it was considered very improbable that so great accuracy could be obtained. Taking the set of observations above in which the main current was 0.2820 amperes, we find that an error of one-tenth of one per cent would mean possible errors of 0.004 in each measurement of the q 's. The difference obtained on reversal of the magnetic field is 0.030. The error in w might then be 25 per cent. The possible error would be greater in the case of some sets of observations where the amount of sodium hydroxide formed was less than in the above case. In general in the above table smaller values of q correspond to smaller values of I . The error in the measurement of w would therefore in general be greater for the series in which I is small. Accordingly, the values of w obtained from the above table for different values of I seem to the present writer to be not very reliable, particularly in the case of the smallest values of I . There is an obvious error in the record of the results given for the primary current 0.0000285.

The present writer used in his measurements the same general method as that adopted by Professor Hall and described in the account of the latter's work at the beginning of this paper.

In order to measure the transverse current with more accuracy, the present writer made a sensitive Thomson galvanometer of low resistance.

DESCRIPTION OF ASTATIC GALVANOMETER.

The general plan followed in constructing this galvanometer was that which Paschen describes in the *Zeitschrift für Instrumentenkunde*, 1893. In order to make the suspension nearly astatic the more easily, about sixty small magnets were used in the two systems. These magnets were made of fine hair-spring. They were 2 to 3 mm. long and about 0.2 mm. wide. The distance between the systems was 5 cm. A mirror 8 mm. long, 2 mm. wide, and 0.4 mm. thick, was made from glass which had been ground plane on both sides by Zeiss of Jena. A very fine quartz fibre was used to suspend the system, which system as finally used had in the earth's field a period of eight seconds. Number 22 copper wire, Brown and Sharp gauge, was wound on a cone of 1.4 cm. height, the radius of the base being 1.9 cm. This was wound nearly full with wire, so that

the coil and cone made a cylinder 1.5 cm. in height and nearly 1.9 cm. in radius. Four of these coils were used in two branches of two each. The resistance of this arrangement was 2.22 ohms at 16.3° C. By means of a control magnet placed about half-way between the upper and lower systems and 20 to 30 cm. away, the period was increased to give the required sensitiveness. A second control magnet placed nearly two meters away sufficed to direct the system without producing any considerable change of sensitiveness.

With the needle 1.7 m. from the scale, and a period of complete vibration of the needle of 12 seconds, the deflection was 1 mm. for 7.7×10^{-10} amperes.

Considerable difficulty was experienced on account of induced currents from outside electric disturbances, such as those caused by the passage of electric cars in the neighborhood. In reading the deflection of the galvanometer needle, an effort was made to get the mean position of the needle at times when it did not seem to be influenced by these induced currents. To make less the error caused by the wandering of the needle the difference of position on reversal was made large, in nearly every case greater than 18 cm. on the scale. The vibration of the needle when the reading was taken was often as much as 2 cm. or 3 cm. on the scale. To lessen the error, five or seven or sometimes more reversals were made in a single set of observations with given conditions. At first it was attempted, before and after each measurement of the transverse effect, to measure also the direct effect of the electromagnet, about 45 m. away, and of the lead-wires of the magnetizing current, which came within 3 meters of the galvanometer. This effect was small in comparison with the transverse current deflection and could not be measured with certainty.

RESISTANCE OF TRANSVERSE CIRCUIT.

The resistance of the galvanometer was measured on the Carey Foster bridge in comparison with coils of manganin wire of temperature-coefficient 0.00002 per degree centigrade. These coils were made by Mr. Persons and by Mr. Coulson of the Jefferson Physical Laboratory. Some of them were made by direct comparison with standard coils made by Wolff of Berlin and tested at the Physikalisch-Technische Reichsanstalt. The other coils were made by indirect comparison with these standard coils. All such coils of manganin wire made in the above way by Messrs. Persons and Coulson are referred to in this paper as standard coils.

Two measurements of the resistance of the galvanometer were taken with an interval of four months. The first gave 2.243 ohms at $17.2^{\circ}\text{C}.$; the second, 2.223 ohms at $16.8^{\circ}\text{C}.$ The difference between these values when correction is made for difference of temperature is 0.011 ohms. The second value was used, that having been taken during the period when the determinations of the Hall effect were made. During these determinations a thermometer was kept with its bulb in the interior of the galvanometer case, and the temperature recorded. In making correction for the temperature, the value 0.0039 was used as the temperature coefficient of the copper wire of the coils.

The resistance of the remainder of the secondary circuit was measured frequently, and, in the case where the effect in gold *leaf* with weak currents was being determined, before and after each measurement of the transverse current. The measurement of this resistance was also made on the Carey Foster bridge. With gold of thickness of 0.0002 cm. and above, the variation of the resistance of the gold and of the connecting wires outside the galvanometer did not amount to more than 0.03 ohms. The variations of the resistance in the gold *leaf* will be referred to below. In these resistance measurements much use was made of a box of coils made by Morris E. Leeds and Co. of Philadelphia. The temperature of these coils was noted. They were compared with standard coils. A measurement of the temperature coefficient of the Leeds coils gave + 0.03 per cent per degree centigrade. The other coils used were manganin coils, whose temperature coefficient was given by Messrs. Persons and Coulson as 0.00002 per degree centigrade.

MEASUREMENT OF SENSITIVENESS OF GALVANOMETER.

The sensitiveness of the astatic galvanometer was in almost every case determined before and after each set of consecutive observations of the transverse effect. The following diagram (Figure 3) will explain the arrangement for the measurement of the sensitiveness.

The resistances whose values are given in this figure were standard resistances. Connections were made between them by means of mercury cups set in heavy bronze blocks. A double commutator was used to reverse the current from the storage cell and that from the Carhart-Clark cell simultaneously.

The certificate of the Carhart-Clark cell used as a standard dated from 1896. A similar cell, which had been put up in the same case with it, at the same time, agreed with it to about one-tenth of one per cent. On comparison with a cadmium cell and another Carhart-Clark

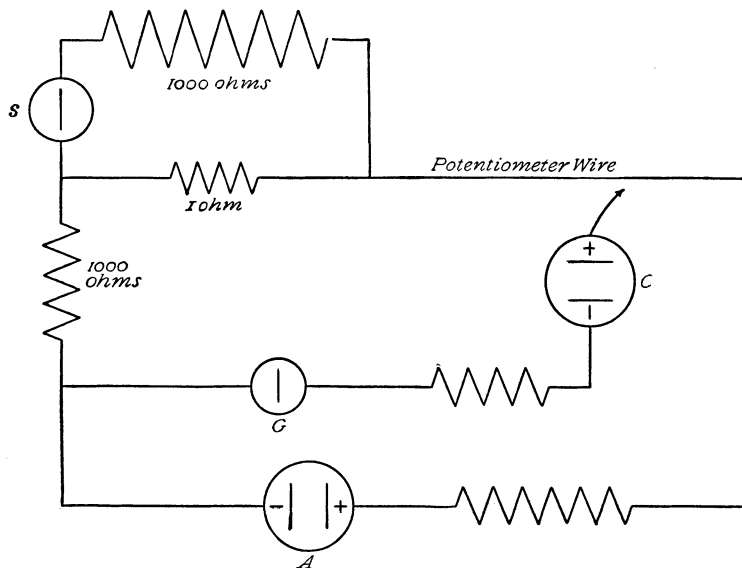


FIGURE 3.

S is the galvanometer whose sensitiveness is to be measured.

C, a Carhart-Clark cell. *A*, storage cell. *G*, a sensitive galvanometer.

cell, both recently put up, the Carhart-Clark cell, which had been used by the writer, was found to have an electromotive force of 1.426 volts at 21°C., instead of 1.437 volts, which was the value derived from the certificate. The value of the *e. m. f.* as corrected by the cadmium cell was used in the calculations below.

MEASUREMENT OF PRIMARY CURRENT.

The primary current, when above 0.01 ampere, was measured with a commercial ammeter which had been corrected at various points as described below. At first a Siemens and Halske ammeter was used; but in most of the measurements in which currents of the above order were used, a Weston ammeter was used in series with the Siemens and Halske ammeter.

For currents from 0.025 ampere up to 0.72 ampere the ammeters were compared with a tangent galvanometer which is described below under the account of the measurement of *H*. In this comparison the 22 turns of wire for which the constant of the galvanometer had been

calculated were used. To correct the ammeters for currents from 0.72 ampere to 2.2 amperes, four turns of wire were wound on the original layer of the tangent galvanometer. As these turns did not fill the breadth of the channels, they were kept in position by wedges of cork placed at frequent distances around the circumferences. Since they could not be made to lie as evenly as the 22 turns which filled the breadth of the channel, the constant for these four turns was determined from the value of H , measured as described below, by passing a current through two copper voltameters in series with the galvanometer. Two measurements of this constant, made with the copper voltameter, using the value 0.1630 for H , gave 1.1920 and 1.1926 respectively. An attempt was made to determine the constant for the four turns from the constant for the 22 turns, as calculated from the dimensions, as follows. A current was sent through the 22 turns and the four turns in series, first in such a way that their effects on the needle agreed, and second in such a way that they were opposed. If G_1 and G_2 be the respective constants,

$$H \tan \theta = \gamma (G_1 + G_2) \text{ for the first case,}$$

and
$$H \tan \theta' = \gamma (G_1 - G_2) \text{ for the second case,}$$

where θ and θ' are the respective deflections, and γ is the current in c. g. s. units.

$$\text{Hence} \quad G_2 = G_1 \times \left\{ \frac{\tan \theta - \tan \theta'}{\tan \theta + \tan \theta'} \right\}$$

The values of θ and θ' were $47^\circ 6'$ and $36^\circ 13'$. G_1 , calculated as described below for the 22 turns, was 6.294. Hence $G_2 = 1.196$, which agrees well with the value for G_2 given above, considering the small difference between θ and θ' and the possible error in the value of H in the previous determinations.

This constant having been determined, the ammeters could be calibrated for currents from 0.72 amperes up to 1.65 amperes for the Siemens and Halske ammeter, and to 2.2 amperes for the Weston. The Weston ammeter was provided with three shunts, the upper limit of the strength of current which could be measured being 0.1 ampere, 1 ampere, and 10 amperes in the three cases. The Siemens and Halske instrument was a milliamperemeter of 1 ohm resistance, reading up to 150 milliamperes. A shunt, of 0.1 ohm resistance, was made of manganin wire. The lead-wires were soldered on the terminals of this shunt coil. By means of this shunt, therefore, the range was extended to 1.65 amperes.

The ammeters were also compared directly with copper voltmeters for positions on the scale in the neighborhood of 1.2 amperes, this portion of the scale being very frequently used. In preparing the voltmeters, the directions followed were in general those found desirable by Gray, as given in Holman's "Laboratory Notes for Use in the Massachusetts Institute of Technology." In accordance with the advice of Ostwald and Luther, a stream of carbon dioxide was kept passing through the solutions during the run. The weights used in measuring the gain of copper were compared with each other and the value of one of them was kindly determined by Professor T. W. Richards in terms of the Washington standard. A table of corrections was made out, these corrections not amounting to more than four hundredths of a milligram, except in the case of the five and ten gram weights, for which the corrections were 0.1 and 0.2 milligrams respectively.

The following results of direct comparison were obtained in the neighborhood of 1.20 amperes.

Current from Copper Deposit.	Reading from Siemens and Halske Ammeter by Shunt Arrangement.	Weston Ammeter.
1.1698	1.177	1.220
1.2064	1.212	1.256

For the Siemens and Halske instrument this was about three-fourths of the full scale reading, for the Weston about one-eighth of the full scale reading.

Primary currents below 0.010 ampere were measured by a potentiometer method. (See Figure 4.) The same Carhart-Clark cell and German silver potentiometer wire were used as in the determination of the sensitiveness of the astatic galvanometer.

The ammeters were also calibrated in the neighborhood of 0.01 ampere to 0.02 ampere by the potentiometer method, as they were sometimes used for measuring primary currents of about this strength. For this calibration they were placed in series in the position corresponding to that of the gold plate in the figure above.

STRENGTH OF THE MAGNETIC FIELD.

The magnetic field was obtained between the poles of a large electromagnet. The pole-pieces were plane and parallel, about 4.2 cm. in diameter and 0.5 cm. from each other. For measuring the strength of the magnetic field, a coil consisting of a single turn of fine wire was jerked out of the field by means of a spring, which was released by means of a long cord pulled by the observer at a ballistic galvanometer. The coil was jerked quickly by the spring to a distance of 34 cm. from the

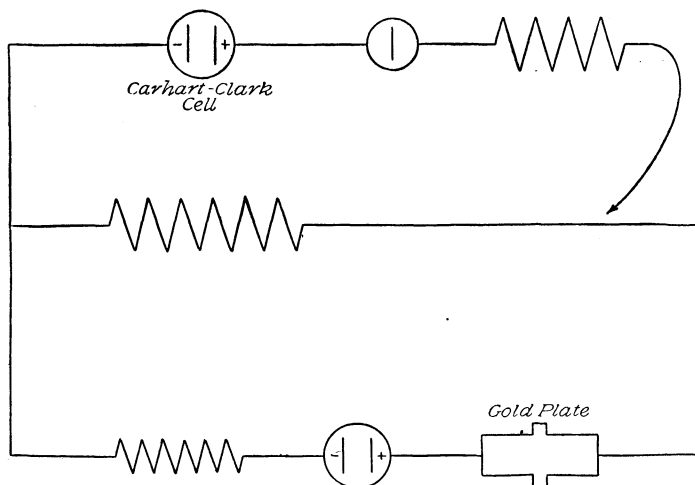


FIGURE 4.

pole-pieces. No appreciable effect was obtained by jerking it from this position to a point 2 meters farther away.

The ballistic galvanometer was situated 8 or 9 meters from the electromagnet. The suspension of this instrument was made of hollow bell-shaped magnets with hard-rubber cores, to give considerable moment of inertia with small damping effect. The mirror was made of a narrow strip of heavy glass. No vane was placed in the suspension, which was supported by a fine quartz fibre. An earth-inductor, in series with the one-turn test-coil mentioned above, was 10 or 11 meters from the electromagnet. It had been wound with six sets of turns by Professor Hall, whose values for the areas of these turns were taken. By making use of one or more of the six sets of turns

in series with the ballistic galvanometer and test-coil, it was possible to get nearly the same deflection by turning the earth-inductor through 180° as by jerking the test-coil from the field, and this was done. The earth-inductor was mounted with its plane vertical and its axis north and south.

DETERMINATION OF H .

The horizontal intensity of the earth's magnetism at the position of the earth-inductor was determined by two methods. In the first method the tangent galvanometer, already referred to, belonging to Professor Hall, was used. This was of the Helmholtz form. There were 11 turns of wire wrapped on each circle. The terms G_2 , G_3 , in Maxwell's* formula were found to be negligible and the constant was given by the expression

$$\frac{2 \pi A^2 n}{(A^2 + B^2)^{\frac{3}{2}}}$$

where A is the radius of the coils, B one-half the mean distance between the coils, and n the number of turns in the two circles. The constant so obtained was 6.294.

A current was passed through two copper voltameters and the tangent galvanometer in series. The galvanometer deflection was 41° . The value given by Ostwald and Luther, 0.000329 gm., was used as the amount of copper deposited by the passage of one coulomb of electricity. This method gave for H 0.1628 c. g. s. units. H was measured also by Gauss's method,† which gave 0.1632.

PREPARATION AND USE OF GOLD STRIPS.

In the following account of the writer's observations, most of the preliminary work is given, as well as that to which more weight is attached. The various improvements which increased the reliability of the measurements are briefly mentioned. The dates on which the work was performed (in the case of the first and fourth sets only approximate) are given.

At first an attempt was made to measure the Hall effect in thicker gold than had been previously used for such measurements. A strip of gold

* Maxwell's "Electricity and Magnetism," Vol. 2, § 700.

† The writer is indebted to Professor B. O. Pierce for the apparatus for the measurement by Gauss's method and for the means of comparison of the resistances used with standard resistances.

about 0.25 mm. thick was obtained from Drew, a gold-beater in Boston. It was stated by him to be very pure. Its density was determined by weighing in and out of water at a known temperature, and was found by this method to be 19.27 relatively to water at 4° C. From this gold two crosses, called hereafter Plate 1 and Plate 2, were cut about 3 cm. long and 1.1 cm. wide. Contact was made at both the primary and the secondary electrodes by electroplating with copper. The gold was fastened on a glass plate with a mixture of resin and beeswax. The plate was placed in a tank through which a current of water was kept flowing. A thermometer was kept in this tank, and the temperature noted.

The currents, the resistances, and strengths of the magnetic fields were measured as described above. The last mentioned measurement was taken before and after each series of measurements of the Hall effect with Plate 1. The strength of the magnetizing current was not read, however, during the measurements of the transverse effect in the case of this plate.

The thickness of the plates was estimated by weighing, the value of the density mentioned above being used, and was also measured with the calipers. The effective thickness was taken as the thickness of the plates between the secondary electrodes. The ratio of this thickness to the average thickness was obtained, therefore, by means of the calipers, while the average thickness was obtained by weighing.

In the following tables,

- i is the transverse current in amperes,
- R is the resistance of the transverse circuit in ohms,
- e is the transverse electromotive force in volts,
- I is the main current in amperes,
- M is the strength of the field in c. g. s. units.

The value of $\frac{ed}{IM}$ is given in c. g. s. units.

APRIL 23. PLATE 1; THICKNESS 0.0238 CM.

i .	R .	e .	I .	M .	$\frac{ed}{IM}$ (c.g.s. units).
6.4×10^{-8}	3.93	2.5×10^{-7}	1.01	7970	0.00074
5.1×10^{-8}	3.94	1.99×10^{-7}	0.822	7910	0.00073
6.8×10^{-8}	3.93	2.66×10^{-7}	1.30	7680	0.00063
1.77×10^{-8}	3.93	6.9×10^{-8}	0.280	7450	0.00079

This gives for $\frac{ed}{IM}$ 0.000722.

In these measurements the strength of the magnetic field fell off rapidly at the last. There was also a possibility that these first measurements were affected a few per cent by short circuiting of a part of the potentiometer wire.

Another series of measurements was taken with Plate 2 of the same gold. In this series the magnetizing current was read at frequent intervals during the time of measurement of the transverse effect. This series gave the following results:

MAY 16. PLATE 2; THICKNESS 0.0234 cm.

<i>i.</i>	<i>R.</i>	<i>e.</i>	<i>I.</i>	<i>M.</i>	$\frac{ed}{IM}$ (c.g.s. units)
8.28×10^{-8}	3.96	3.28×10^{-7}	1.535	6990	0.000716

The series of measurements on the second plate is believed to be the more reliable, because of the method employed to measure the magnetic field, and because of the steadier conditions of the galvanometer.

The values obtained above agree well with the value 0.00071 obtained by Von Ettingshausen and Nernst* in what they considered their best measurement. In the paper referred to the thickest gold used was 0.00392 cm. thick. The strength of the main current is not given by them.

In the remaining experiments, which were made with thinner gold, it was attempted to get as great a range of primary current as possible. Observations of the Hall effect were taken with weak and strong primary currents alternately, except in the first set of observations given below.

Plate No. 3 was made of gold supplied by Nickolds, of Brooklyn, N. Y., and said by him to be pure ("1000 fine"). By weighing, the average thickness was estimated to be about 0.00018 cm. A plate was made of the same form as Plates 1 and 2, and cemented on the glass plate with a mixture of resin and beeswax. The connection with the electrodes was made as before by electroplating with copper. In doing this, the surface of the gold was accidentally punctured at one or two points, which fact, together with the uncertainty as to local thickness in so thin a sheet, made the plate unfit for measurement of the absolute value of the Hall effect, but did not injure it for a test of the variation of

* Akademie der Wissenschaften, Wien, 94, 2, 602 (1886).

the transverse effect with the primary current. The observations were taken in the same manner as with Plate 1. The first set of observations, in which the main current, I , was increased by steps from 0.02 ampere to 1.59 amperes, gave the following results:

APRIL 30. PLATE 3; THICKNESS 0.000184 CM.

i .	R .	e .	I .	M .	$\frac{ed}{IM}$ (c.g.s. units).
1.11×10^{-7}	3.965	4.42×10^{-7}	0.0200	6210	0.000655
1.50×10^{-7}	6.965	1.05×10^{-6}	0.0504	6200	0.000617
1.31×10^{-7}	43.96	5.77×10^{-6}	0.277	6196	0.000618
2.14×10^{-7}	103.77	2.22×10^{-5}	1.064	6210	0.000615
1.72×10^{-7}	203.8	3.50×10^{-5}	1.591	6180	0.000656

As these results were somewhat irregular, it was determined to make measurements with weak and strong currents alternately. In the following set of measurements the readings of the ammeters for the weak current were taken at about one-sixth of the full scale reading for the Weston ammeter, and about one-tenth of the full scale reading for the Siemens and Halske ammeter.

MAY 7. PLATE 3.

i .	R .	e .	I .	M .	$\frac{ed}{IM}$ (c.g.s. units).
9.94×10^{-8}	3.958	3.93×10^{-7}	0.0158	7320	0.000626
1.37×10^{-7}	204.0	2.79×10^{-5}	1.130	7330	0.000621
9.70×10^{-8}	3.99	3.87×10^{-7}	0.0157	7230	0.000629
Means					0.00062 0.00063

On account of the position of the ammeter scale readings for weak currents, these measurements are not considered as accurate as the succeeding measurements.

Plate No. 4 was very kindly prepared by Professor Hall. The method adopted was the same as that in preparation of the plate in which the phenomenon was discovered. A glass plate was covered with a thin

layer of shellac dissolved in alcohol. The alcohol was allowed to evaporate. Then the plate was heated and pressed on the thin gold leaf. A strip about 7 cm. long and 1.5 cm. wide was cut from this, with two short arms for the secondary electrodes as described at the beginning of this paper. Contact with the electrodes was made by pressing polished brass pieces on tin-foil in contact with the gold. The brass pieces were kept in place by a cement of resin and beeswax, which also prevented the water from reaching the electrodes. The gold was then covered with a thin layer of paraffin.

The first two sets of observations gave the following results:—

MAY 9. PLATE 4.

<i>i.</i>	<i>R.</i>	<i>e.</i>	<i>I.</i>	<i>M.</i>	$\frac{ed}{IM}$ (c.g.s. units.)
6.04×10^{-8}	12.30	7.43×10^{-7}	0.00142	7240	72.2
1.52×10^{-7}	3009.3	4.58×10^{-4}	0.780	7390	79.5

MAY 11. PLATE. 4.

<i>i.</i>	<i>R.</i>	<i>e.</i>	<i>I.</i>	<i>M.</i>	$\frac{ed}{IM}$ (c.g.s. units.)
4.74×10^{-8}	8.85	4.20×10^{-7}	0.000712	7440	79.2
6.59×10^{-8}	10015	6.59×10^{-4}	1.21	7440	73.4
4.96×10^{-8}	8.857	4.40×10^{-7}	0.000712	7440	82.9
Means					73.4 81.0

Hitherto in almost every case the magnetic field had been measured before and after each measurement of the transverse effect for a given strength of primary current. This required the removal of the plate from the field at every change from weak to strong or strong to weak in the primary current. Hereafter direct determinations of the strength of the magnetic field by means of the test coil were made only at the beginning or end, generally at both the beginning and end, of each period of work, which included one or more changes from strong to weak or weak to strong of primary current.

MAY 12. PLATE 4.

<i>i.</i>	<i>R.</i>	<i>e.</i>	<i>I.</i>	<i>M.</i>	$\frac{e}{IM}$
8.51×10^{-8}	8.92	7.59×10^{-7}	0.00142	7260	73.8
1.29×10^{-7}	5011	6.46×10^{-4}	1.21	7260	73.6
9.02×10^{-8}	8.80	7.94×10^{-7}	0.00142	7260	77.1
1.38×10^{-7}	5010	6.90×10^{-4}	1.21	7260	78.6
Means					76.1 75.5
9.49×10^{-8}	8.88	8.43×10^{-7}	0.00142	7180	82.9
1.32×10^{-7}	5010	6.60×10^{-4}	1.20	7190	76.5
9.33×10^{-8}	8.91	8.32×10^{-7}	0.00142	7210	81.3
Means					76.5 82.1

In the next two sets the magnetizing current was read at intervals during the measurement of the transverse effect, and corrections for change of field were made accordingly. A measurement of the resistance of the transverse circuit was made before and after each measurement of the transverse effect when the weak values of *I* were used.

In passing from one set to another the gold was in nearly every case removed from the bath, and remained out many hours.

MAY 13. PLATE 4.

<i>i.</i>	<i>R.</i>	<i>e.</i>	<i>I.</i>	<i>M.</i>	$\frac{e}{IM}$
8.89×10^{-8}	8.88	7.89×10^{-7}	0.00142	7360	75.6
1.30×10^{-7}	5010	6.50×10^{-4}	1.19	7330	74.4
8.96×10^{-8}	8.88	7.95×10^{-7}	0.00142	7270	77.2
1.31×10^{-7}	5010	6.55×10^{-4}	1.178	7250	76.7
9.24×10^{-8}	8.93	8.25×10^{-7}	0.00142	7260	80.3
Means					75.6 77.7

MAY 14. PLATE 4.

9.26×10^{-8}	8.85	8.19×10^{-7}	0.00142	7240	79.9
1.30×10^{-7}	5010	6.54×10^{-7}	1.174	7200	77.3
9.70×10^{-8}	8.82	8.56×10^{-7}	0.00142	7160	84.4
Means					77.3 82.2

In the case of the gold *leaf* no value for the thickness has been given. When a calculation of the thickness is made from the dimensions of the strip (6.2 cm. long and 1.5 cm. wide) and its resistance (3.8 ohms), one obtains 2.3×10^{-6} cm. as a result. This is based on the value 2.15×10^{-6} ohms as the specific resistance of gold. This value is probably not quite accurate, since it was the custom of the gold-beater from whom the leaf was obtained to use an alloy containing about 96 per cent of gold, 2 per cent of silver, and 2 per cent of copper. It was not at all uniform in thickness, as could be seen even with examination by the naked eye. Again, in very thin sheets of metal the electrical resistance increases very rapidly as the thickness is diminished.* The above value of the thickness is therefore not given as in any sense accurate. When it is used to estimate the Hall effect in the case of Plate 4, the value 0.000181 is obtained, that is about one fourth the value obtained in the case of the thicker gold plates 1, 2, and 3.

It is also to be remembered that Moreau, quoted above, found in the case of silver (and nickel) that the Hall effect diminished rapidly with thicknesses below 50 millionths of a millimeter. It seems probable that the Hall effect in gold diminishes in the same way.

Two additional sets of observations were made on Plate 3, the potentiometer method (see Fig. 4) being adopted to measure the main current. As in the case of the later measurements on Plate 4 the plate was kept in the same position during a set of consecutive measurements, including changes from weak to strong main current, or *vice versa*; but frequent readings of the magnetizing current were taken, and thus the changes of the magnetic field observed.

* Ettingshausen, *Sitzungsberichte Akad. Wien*, **81**, 446 (1880); A. C. Longden, *Physical Review*, **11**, 84-94 (1900); J. J. Thompson, *Cambridge Proc.* (2), **9**, 120-122 (1901).

JUNE 20. PLATE 3.

<i>i.</i>	<i>R.</i>	<i>e.</i>	<i>I.</i>	<i>M.</i>	$\frac{ed}{IM}$ (c.g.s. units).
1.09×10^{-7}	3.99	4.34×10^{-7}	0.0168	7360	0.00065
1.05×10^{-7}	304.0	3.20×10^{-5}	1.23	7360	0.00065
1.11×10^{-7}	3.99	4.43×10^{-7}	0.0168	7350	0.00066
1.01×10^{-7}	304.0	3.08×10^{-5}	1.23	7350	0.00063
Means					0.00064 0.000655

The following set differs from all the other measurements in this paper in the method of reading the galvanometer. Instead of attempting to pick out times when the galvanometer needle was not affected by outside disturbances, the experimenter determined each position of the index by taking the mean of several (usually six) instantaneous observations made at regular intervals, about 8 seconds, as measured by the metronome. Five such determinations of the position of the index were made in a single test, three with the magnetic field in one direction and two with the field in the opposite direction. The following results were obtained.

JUNE 23. PLATE 3.

<i>i.</i>	<i>R.</i>	<i>e.</i>	<i>I.</i>	<i>M.</i>	$\frac{ed}{IM}$ c.g.s. units.
1.13×10^{-7}	3.96	4.46×10^{-7}	0.0168	7390	0.00066
1.10×10^{-7}	304.0	3.34×10^{-5}	1.23	7370	0.00068
1.10×10^{-7}	3.96	4.37×10^{-7}	0.0168	7330	0.00065
1.05×10^{-7}	304.0	3.18×10^{-5}	1.23	7300	0.00065
1.24×10^{-7}	3.96	4.92×10^{-7}	0.0168	7320	0.00074
1.07×10^{-7}	304.0	3.25×10^{-5}	1.23	7300	0.00067
1.22×10^{-7}	3.96	4.82×10^{-7}	0.0168	7290	0.00073
1.15×10^{-7}	304.0	3.51×10^{-5}	1.22	7290	0.00073
Means					0.00068 0.000695

The larger absolute values of the Hall effect obtained here may have been due to a smaller air-gap between the magnet poles than in the preceding measurements. The strength of the magnetic field was measured before this last set, but not, as had been previously the custom, after it also. As the wedging, intended to keep a constant width of the gap, was generally changed during the removal of the plate from the gap, some differences between the sets of measurements might be expected from this cause. In the case of all measurements later than May 7 the wedging was left unchanged by the experimenter during a set of consecutive measurements involving changes from weak to strong main current or *vice versa*.

The following table gives the values of the current density used in each set of observations on each plate, and the corresponding values of the Hall effect. In the case of Plate 4, as explained above, the value of the thickness given, being calculated from the resistance, is not considered accurate. The current density is given in c.g.s. electromagnetic units of current per square centimeter of cross section of plate. The Hall effect is given as above in c.g.s. units.

		Current Density.		Hall Effect.
Plate 1	April 23	{	3.9	0.00074
			3.1	0.00073
			5.0	0.00063
			1.07	0.00079
Plate 2	May 16		6.0	0.00071
Plate 3	April 30	{	10.9	0.00066
			27.4	0.00062
			151.	0.00062
			580.	0.00062
			860.	0.00066
Plate 3	May 7	{	8.6	0.00063
			610	0.00062
	June 20	{	9.1	0.000655
			670	0.00064
	June 23	{	9.1	0.000695
			670	0.00068
			0.000647	0.000660

		Current Density.		Hall Effect.
Plate 4	May 9	{ 40		0.000169
		{ 22000	0.000186	
	May 11	{ 20		0.000190
		{ 34000	0.000172	
	May 12	{ 40		0.000176
		{ 34000	0.000178	
		{ 40		0.000192
	May 13	{ 34000	0.000179	
		{ 40		0.000182
	May 14	{ 34000	0.000177	
		{ 40		0.000192
			0.000181	
			0.000179	0.000184

CONCLUSIONS.

Moretto's method is defective and subject to large errors. His conclusion as to the effect of current density is given apparently as a general property of metals. This is an unwarranted inference from the evidence given in his paper, which does not specify the metals worked upon in obtaining the table reproduced above.

The writer's work on gold appears to indicate a very small increase in the Hall effect for the weaker values of the main current, as in a decided majority of the sets of observations the Hall effect comes out a little larger for the weaker values of the main current. The difference is perhaps within the limits of error. It may possibly be a result of the large stresses in thin gold due to the expansion and contraction of the paraffin and cements. Under the influence of the heating due to the strong currents, these stresses might be of a different order of strength from the stresses when a very weak current is flowing. There might therefore be some difference in the properties of the metals in the two cases.

The writer proposes to continue the investigation, using also some other metals.

The writer desires to express his gratitude to Professor Hall for constant advice and personal aid, and to him and to the other professors of the physical department for the kindly loan of the apparatus for the work.